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Federal Communications Commission
Office of the Secretary

Dear Mr. Thomas:



BOSTON
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TWIN CITIES
WASHINGTON, DC

Attached is a Petition on behalf of Multi-band OFDM Alliance Special Interest Group (MBOA-SIG) requesting a waiver of certain measurement procedures and policies for MB-OFDM ultra-wideband devices. The MBOA-SIG represents 162 domestic and foreign companies seeking IEEE adoption of a standard for the next generation of short-range broadband wireless technology. As discussed in the Petition, a waiver will permit MB-OFDM technology to compete on an equal footing in the marketplace with other ultra-wideband technologies.

Please call us if you have any questions.

Very truly yours,

Terry G. Mann
Robert J. Ungar

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Before the
Federal Communications Commission
Washington, D.C. 20554

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Federal Communications Commission
Office of the Secretary

In the Matter of)
Request for Waiver of Measurement) File No.
Procedures for OFDM Ultrawideband Devices)

PETITION FOR WAIVER

The Multi-band OFDM Alliance Special Interest Group (MBOA-SIG), including Intel Corporation, Texas Instruments, Staccato Communications, Alereon Inc., and Wisair, through its counsel, hereby requests a waiver of certain measurement procedures that may apply to multi-band orthogonal frequency division multiplexing (MB-OFDM) ultra-wideband (UWB) systems. The purpose of this waiver request is to ensure that MB-OFDM systems are allowed to compete on a "level playing field" with pulse-based UWB systems so that the market can decide which of these emerging technologies will best serve the public's need.

Background

MBOA-SIG represents a growing membership of 162 domestic and international companies seeking IEEE adoption of a MB-OFDM standard for the next generation of short-range, broadband wireless technology for residential and commercial use.¹ The MB-OFDM architecture features three non-overlapping carriers operating between 3432 MHz and 10296 MHz. Each carrier transmits QPSK-modulated OFDM symbols, or pulses, in a 528 MHz bandwidth and thus meets the Commission's minimum UWB bandwidth requirements. MB-OFDM systems are designed to operate in one of four modes, the simplest of which is depicted in Figure 1 below.² Digital information is

¹ IEEE 802.15 Task Group 3a is evaluating physical layer standards for wireless personal area networks (WPANs) utilizing UWB technology.

² The other three modes are set forth in Attachment A.

transmitted in a time inter-leaved fashion so that every UWB pulse is approximately 240ns long with each in-band interval between pulses approximately 700ns long.³ In this mode, the MB-OFDM system transmits data sequentially in each non-overlapping band, repeating the band sequence until the transmission is complete.⁴

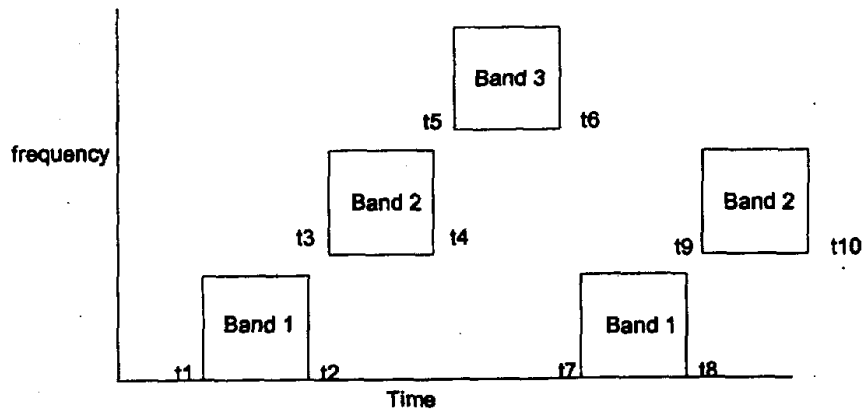


Figure 1

The MB-OFDM architecture presents certain advantages over pulsed-based UWB systems. For example, MB-OFDM systems produce lower out-of-band emissions in critical government bands and are inherently more flexible in their ability to avoid potential sources of interference. MB-OFDM systems also improve multipath capture and provide flexibility in balancing performance against implementation complexity.⁵ As a result, MB-OFDM has gained widespread support among manufacturers and service providers throughout the world. Nonetheless, the marketplace deployment of MB-OFDM systems faces unintended regulatory hurdles that threaten to stifle this exciting new technology.

³ The exact time of each pulse is 242.4ns of "on" time followed by a 695.1ns "off" period for a total pulse plus interval time period of 937.5ns.

⁴ Details on the MB-OFDM waveform are contained in Attachment B. Additional information on the MB-OFDM architecture can be found in the document *IEEE 802.15-04/0220* at <http://www.802wirelessworld.com/index.jsp>

⁵ Advantages of one UWB architecture over another is a source of industry debate and is a function of many factors including time to market, complexity, cost, performance, range and scalability.

The issue presented by this petition is the method by which average radiated emissions are to be measured for MB-OFDM systems under the UWB rules.⁶ In discussions with the Office of Engineering and Technology staff it was made clear to MBOA-SIG members that the UWB test procedures had been developed specifically with pulse-based systems in mind and hence, the application of these procedures to MB-OFDM systems was less than certain. The staff also indicated that any clarification or waiver of these test procedures would depend, fundamentally, on whether MB-OFDM systems could be shown to cause no greater harmful interference to licensed services than pulsed UWB.⁷ To address this concern, MBOA-SIG members conducted simulated and actual interference testing with representative samples of OFDM and pulsed UWB devices to determine their comparative interference potential. Set forth in Section III below are the results of such tests which demonstrate conclusively that MB-OFDM systems, measured under normal operating conditions, pose no greater threat of harmful interference than pulsed UWB systems permitted by the rules.⁸

Based on these test results and the analysis which follows, MBOA-SIG seeks a waiver of the Commission's frequency hopping measurement procedures to allow MB-OFDM systems to be tested for average emissions under normal operating conditions, rather than with band sequencing stopped. Additionally, MBOA-SIG seeks a waiver of the pulse "gating" procedures set forth in Section 15.521(d) of the rules to the extent that these procedures apply to MB-OFDM systems. A waiver of these test procedures will serve the public interest, as it will permit MB-OFDM systems to compete fairly for public acceptance in the market, without increasing the threat of interference from UWB devices.

⁶ In a July 2003 Petition for Declaratory Ruling filed by Motorola and Xtreme Spectrum, the Commission was also asked to rule on the correct test procedures for MB-OFDM. In addition, this issue was addressed in a July 2003 white paper submitted to the IEEE by Xtreme Spectrum.

⁷ The Commission recently approved a pulsed UWB communication device. See FCC ID: RUN-XSUWBWDK, August 9, 2004.

⁸ The FCC Lab is also testing representative samples of MB-OFDM and pulse-based UWB devices but the test results were not available as of this filing date.

Waiver Standards

The standards for obtaining a waiver of the Part 15 rules are well established: an applicant must show that a grant of the waiver is in the public interest and does not increase the risk of harmful interference.⁹ More generally, Section 1.3 of the Commission's rules provides that the rules may be waived "for good cause shown." In the licensed services, the Commission has waived its rules when the underlying purpose of those rules would not be served or would be frustrated by application to a specific case; or, in view of unique factual circumstances, an application of the rules would be unduly burdensome or contrary to the public interest.¹⁰ As the following discussion will demonstrate, MBOA-SIG's request inarguably meets these tests.

I. The Commission's Frequency Hopping Test Procedures Are Not Intended to Apply to MB-OFDM Systems.

Section 15.521(d) requires UWB radiated emissions above 960 MHz to be measured using an RMS average detector. Under Commission test policies, average emissions from "frequency hopping systems" are generally required to be measured with the frequency hopping function disabled.¹¹ Applied to MB-OFDM systems, however, such policies would mean that RMS average measurements could not factor in the transmission "off" intervals, thereby requiring average power levels for these systems to be considerably less than what the UWB rules allow. The question then, is whether the frequency hopping test procedures are intended to apply to MB-OFDM systems.

⁹ See *In the Matter of Part 15 of the Commission's rules to Relax the Technical Limitations Imposed on the Operation of a Low Power communication Device in the AM Broadcast Band*, 45 F.C.C. 2d 360 (1974); *In the Matter of Dairy Systems Division of DEC International Inc. Waiver of Part 15 Subpart D to Permit Operation of a Low Power Communication System on 2.5 MHz and 6.0 MHz for the Purpose of Identifying Individual Cows in the Herd*, 87 F.C.C. 2d 413 (1981).

¹⁰ See *WAIT Radio v. FCC*, 418 F.2d 1153 (D.C. Cir. 1969) in which the court held that it would be permissible to waive a rule which does not take into account "effective implementation of overall policy." *Id.* at 1159. See also, *Northeast Cellular Telephone Company, L.P. v. FCC*, 897 F.2d 1164 (D.C. Cir. 1990).

¹¹ See FCC Public Notice of March 30, 2000 DA 00-705, Filing and Measurement Guidelines for Frequency Hopping Spread Spectrum Systems ("FHSS Public Notice"). The Commission has also taken the position, in a June 2003 waiver granted to Siemens VDO Automotive (see fn. 26 *infra*), that Section 15.31(c) requires frequency hopping to be stopped. This interpretation of Section 15.31(c), however, is somewhat dubious given that the rule only discusses swept-frequency devices.

A careful examination of the frequency hopping test procedures indicates that they have never been applied outside the context of the spread spectrum rules. Part 2 of the Commission's rules specifically defines frequency hopping as a type of "spread spectrum" emission,¹² and Part 15 sets forth the requirements for unlicensed spread spectrum hopping devices. To the extent that any transmission system -- UWB or otherwise -- is categorized as "frequency hopping," it would have to be in the context of these requirements.¹³ Of particular relevance in this regard is Section 2.1, which states in pertinent part:

The test of a frequency hopping system is that the near term distribution of hops appears random, the long term distribution appears evenly distributed over the hop set, and sequential hops are randomly distributed in both direction and magnitude of change in the hop set.

MB-OFDM systems, however, do not meet this threshold test. The three bands used in all MB-OFDM systems are "sequenced" according to one of four deterministic and fixed hopping patterns,¹⁴ rather than randomly in direction and magnitude as contemplated by the rules. Moreover, because MB-OFDM systems also feature "digital modulation" techniques¹⁵ the rules for frequency hoppers are inapplicable. A recent Commission guideline on hybrid spread spectrum systems confirms that a digital modulation device, even one that hops, is not required to follow the rules or test procedures for frequency hopping systems.¹⁶

¹² See Section 2.1 of the Commission's Rules.

¹³ A system, which changes frequencies periodically or regularly, may or may not be defined as "frequency hopping" depending on the nature of the system. Indeed, many systems today use cognitive radios to change frequencies on a regular basis to avoid interference yet are not considered by the Commission to be spread spectrum frequency hoppers. While Section 15.247 explains the specific attributes of a spread spectrum frequency hopping systems it clearly does not (and was not intended to) apply to MB-OFDM.

¹⁴ See Attachment A for the different MB-OFDM operating modes.

¹⁵ See Section 15.403.

¹⁶ Various manufacturers had asked the FCC Lab to clarify the rules for a product which features both frequency hopping (FHSS) and digital modulation (DTS) characteristics. In a clarification letter dated December 9, 2001, the Commission states in relevant part, "[w]e will allow a manufacturer of a combination DTS and FHSS system to demonstrate compliance with the rules [for one or the other]. There is no need to demonstrate compliance with both the FHSS standards and the DTS standards." See http://hraunfoss.fcc.gov/eas_public/SilverStream/Pages/pg_fts_frameset2i_search_fcc_gov2.html In addition, the Commission recently ruled, *In the matter of Modification of Parts 2 and 15 Rules for Unlicensed Devices*, Report & Order, ET Docket 03-201, FCC 04-165 (released July 12, 2004), that DTS systems may be measured in average mode, citing the procedures set forth in an August 2002 Public Notice (DA-02-2138) for U-NII devices. These procedures stand in direct contrast to the test procedures for frequency hopping devices by providing that "transmission power may be averaged across symbols over an interval of time equal to the transmission pulse duration of the device or over successive pulses." In other

Although the Commission's UWB Order addresses frequency hoppers in passing, it is in the context of the minimum bandwidth requirements and not in terms of any specific test procedures.¹⁷ In paragraph 32 of the UWB Order where hopping is discussed, the Commission notes that it is "unlikely that frequency hopping systems would comply [with the fractional or minimum bandwidth requirement] unless an extremely wide bandwidth hopping channel is employed." The Commission's concern was addressed to conventional spread spectrum hoppers that employ narrowband emissions over large areas of the spectrum. By requiring that frequency hopping be disabled, the Commission was intending to make certain that narrowband hoppers (those with a per hop bandwidth much less than 500 MHz) would not meet the definition of UWB. But this is a non-issue for MB-OFDM systems because each band that is sequenced complies fully with the UWB minimum bandwidth requirements.

Thus, there was no intent on the Commission's part, pursuant to either its frequency hopping test policies or its UWB Order, to impose special test requirements on MB-OFDM systems. Accordingly, MBOA-SIG respectfully requests the Commission to waive these policies and permit MB-OFDM systems to be measured in their normal operating mode.¹⁸

II. The "Gating on" Requirement in Section 15.521(d) was Never Intended to Apply to MB-OFDM Systems.

A related measurement issue is the applicability to MB-OFDM systems of the "gating on" requirement in Section 15.521(d). In relevant part this test procedure provides:

words, testing under normal operating conditions is specifically allowed for DTS systems, even those which hop among frequency bands like MB-OFDM.

¹⁷ See *In the Matter of Ultra-Wideband Transmission Systems*, First Report and Order, ET Docket 98-153, 17 FCC Rcd 7435 at para. 32, released April 22, 2002.

¹⁸ Where measurements are required to be made with hopping disabled, the FHSS Public Notice (at page 6) permits a duty cycle correction of $20 \log(\text{dwell time}/100\text{ms})$ to be applied to average readings. This is consistent with the treatment for other Part 15 pulsed emitters (see Section 15.35(c)). Accordingly, if MB-OFDM systems are to be treated as frequency hoppers whose emissions must be measured with band sequencing disabled, Commission testing policies permit average emission levels to be corrected for the band sequencing duty cycle.

if pulse gating is employed, where the transmitter is quiescent for intervals that are long compared to the nominal pulse repetition interval, measurements shall be made with the pulse train gated on.

On its face, this test would appear to have the same effect for MB-OFDM systems as the disabling of the band sequencing function. With sequencing stopped, RMS measurements could not take into account the in-band transmission intervals, and the resulting average power levels would be considerably lower than the maximum permitted under the rules. As a result, MB-OFDM systems would be unnecessarily handicapped as compared to other UWB systems. A careful reading of Section 15.521(d), however, reveals that this procedure was never intended to apply to MB-OFDM.

By its wording, the rule applies only to UWB systems which transmit a series of pulses (each series being a “pulse train”¹⁹) that are gated on and off. An example of a gated UWB pulse train is depicted in Figure 2 below.

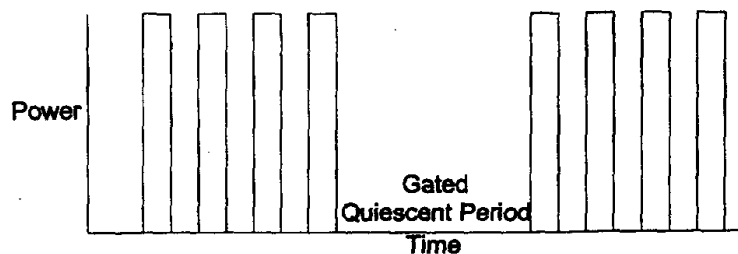


Figure 2

As the figure illustrates, the gating interval between successive pulse trains is the “quiescent” period, which is referenced by the rule. To apply the rule, then, one needs to know whether the gated quiescent period is long compared to the nominal pulse repetition interval. The rules, however, do not define the term “pulse repetition interval” although logically it would mean the time period between the leading edge of one pulse and the leading edge of the next pulse in the same band. For an MB-OFDM transmission, as seen in Figure 1, the pulse repetition interval in Band 1 would be the time between t_1 and t_7 . Similarly, for Band 2, the interval would be the time between t_3 and t_9 , and so on.

¹⁹ Section 15.35(c) defines a pulse train as a series of pulses including any blanking intervals.

Ultimately, the test to be applied under Section 15.521(d) is whether these pulse repetition intervals are short or long as compared to some quiescent period, or gating interval. But in an MB-OFDM system there is no quiescent period because the QPSK-modulated OFDM “pulse train” in each band is never gated on or off.²⁰ With no quiescent period to compare against the MB-OFDM pulse train, this particular test procedure would not appear to apply.²¹ Accordingly, MBOA SIG urges the Commission to waive the gating requirements of Section 15.521(d) to the extent they apply to MB-OFDM so as to permit the average measurements for these systems to be made under normal operating conditions.

III. Test Data Confirms that MB-OFDM Systems Pose No Greater Threat of Harmful Interference Than Pulsed UWB Systems Permitted by the Rules.

To address the question of possible harmful interference, MBOA-SIG members performed a series of technical studies to determine the interference characteristics of the MB-OFDM waveform as compared to other UWB waveforms allowed under Commission rules. First, several bit level simulations were performed to evaluate the impact of MB-OFDM devices on the bit error rate of a representative wideband receiver. The results were then compared to simulations of a pulsed UWB device permitted under the Commission’s rules.²² The simulations clearly demonstrate that an MB-OFDM device will not cause harmful interference and, in fact, is less likely to cause harmful interference than some pulsed UWB emitters.

Second, to validate the simulation studies, measurements were then performed using an actual C-band satellite receiver.²³ As expected, the tests showed the MB-OFDM systems pose a smaller interference threat than pulsed UWB devices. Indeed, for the effects of the device generating the MB-OFDM waveform even to be even perceived, the

²⁰ A QPSK modulated OFDM waveform contains no “off” periods so the continuous QPSK modulated OFDM emission would have to be considered a “pulse” under Section 15.521(d).

²¹ Only if the time period between t_2 and t_7 (see Figure 1) were considered the quiescent period could the language of Section 15.521(d) be applied. However, this interpretation also fails because it would then mean that there is no separate pulse repetition interval against which to compare the quiescent period. In other words, the MB-OFDM pulse train subsumes whatever “quiescent period” otherwise exists.

²² See IEEE 802.15-04/010r1 at <http://www.802wirelessworld.com/index.jsp>.

²³ *Id.* See also, IEEE 802.15-04/013r0 at <http://www.802wirelessworld.com/index.jsp>.

device had to be located within 20 feet of the C-band dish, a situation that would not occur outside a test bed. This test demonstrated that it would be highly unlikely for an MB-OFDM device (or, for that matter, any UWB device operating under the Part 15 limits) to cause harmful interference to C-band operations.²⁴

Finally, MBOA SIG members evaluated the amplitude probability distribution (APD) for the MB-OFDM waveforms and again compared these to pulsed UWB devices permitted under the rules.²⁵ The APD analysis was a tool used extensively by NTIA to determine the potential for interference into generic narrowband systems and seemed useful to analyze the MB-OFDM waveforms. Again, the results clearly demonstrate that a device generating an MB-OFDM waveform presents less of interference than the pulsed UWB emitters permitted by the rules.

IV. A Waiver of UWB Test Procedures for MB-OFDM Systems Will Serve the Public Interest.

A waiver of the test procedures, as requested herein, will serve the public interest by ensuring that MB-OFDM systems are not unfairly burdened in the marketplace and the public is not be denied the full benefits of this innovative new technology. More to the point, a waiver will prevent certain technology-specific test procedures from being woodenly applied to encompass and constrain MB-OFDM. Commission procedures that require band hopping to be disabled or pulse-gating to be kept running are shown, in this Petition, to have been developed specifically for spread spectrum and pulsed UWB systems respectively and not for MB-OFDM. A waiver, therefore, will ensure that these testing policies do not serve to frustrate the emergence of this important new UWB technology.

A waiver will also advance the Commission's goal of fostering competition among unlicensed wireless systems including UWB.²⁶ This is not a theoretical concern. It must be emphasized that a growing coalition of over 160 companies is poised to offer

²⁴ Additional measurements of interference from MB-OFDM devices can be found in a contribution to the ITU from the Development Authority of Singapore (IDA). See Document 1-8/95-E, June 1, 2004.

²⁵ *Id.* at fn 1, *supra*. See also IEEE 802-15-04/326r0 at <http://www.802wirelessworld.com/index.jsp>.

²⁶ On June 25, 2003, the Chief Engineer granted Siemens VDO Automotive a waiver of Rule 15.31(c) for a pulsed, frequency hopping UWB vehicular radar system to permit testing of this system with the hopping function active.

MB-OFDM devices to consumers in the very near future based on the clear benefits of this technology. A grant of the requested waiver will enable robust competition between emerging UWB technologies and ensure that the marketplace, rather than government regulations, determines which of these technologies best serves the public's communications needs.

Moreover, the underlying purpose of the Commission's test policies will not be undercut by a grant of this waiver request. Measurement policies, which require frequency hopping systems to be measured with the hopping disabled and pulsed systems with gating on, are designed fundamentally to prevent harmful interference. As demonstrated through comparative testing, however, MB-OFDM systems operating under normal conditions at the maximum allowed average power levels pose no greater risk of harmful interference than pulse-based UWB systems. The shortsighted implementation of certain measurement policies, therefore, threatens to hamper MB-OFDM technology unduly, with no corresponding benefit to the public.²⁷

Finally, it should be emphasized that the waiver being sought herein is limited in scope. It is intended to apply only to the specific MB-OFDM architecture that has been tested – a three carrier non-overlapping system with each carrier exceeding the UWB minimum bandwidth requirement.²⁸ In view of the unique factual circumstances presented in this case, MBOA-SIG submits that a waiver will clearly serve the public interest.

Conclusion


For the reasons set forth above, the Commission is respectfully requested to waive its test procedures that require MB-OFDM systems to be measured, in

²⁷ The administrative history of the UWB rulemaking bears this out. The "gating rule" in Section 15.521(d) comes from a January 2001 study prepared by NTIA (see NTIA Special Publication 01-43, *Assessment of Compatibility Between Ultrawideband Devices and Selected Federal Systems* (January 2001)) in which NTIA noted that no peak power limits or measurement procedures had been adopted for UWB devices and expressed concern that "if RMS average is measured over the gating period [it] could result in a higher peak to average ratio." *Id.* pp. 2-3 and 3-9. Accordingly, NTIA sought to have a gating rule imposed to control high levels of potentially harmful peak emissions. However, the UWB rules eventually adopted by the Commission established absolute limits on peak emissions (see e.g. Section 15.517(e)), thereby negating any need for a separate gating rule. Thus, the rule exists today more as an artifact of the rule making process than a means of preventing harmful interference.

²⁸ The waiver would apply to the four time frequency codes set forth in Figure 1 and Attachment A.

RMS average mode, with band sequencing disabled and instead, permit such systems to be measured under normal operating conditions. Such a waiver will serve the public interest, as it will enable MB-OFDM systems to achieve their full potential in the market and compete for public acceptance without any increased risk of harmful interference from UWB devices.

Respectfully Submitted,



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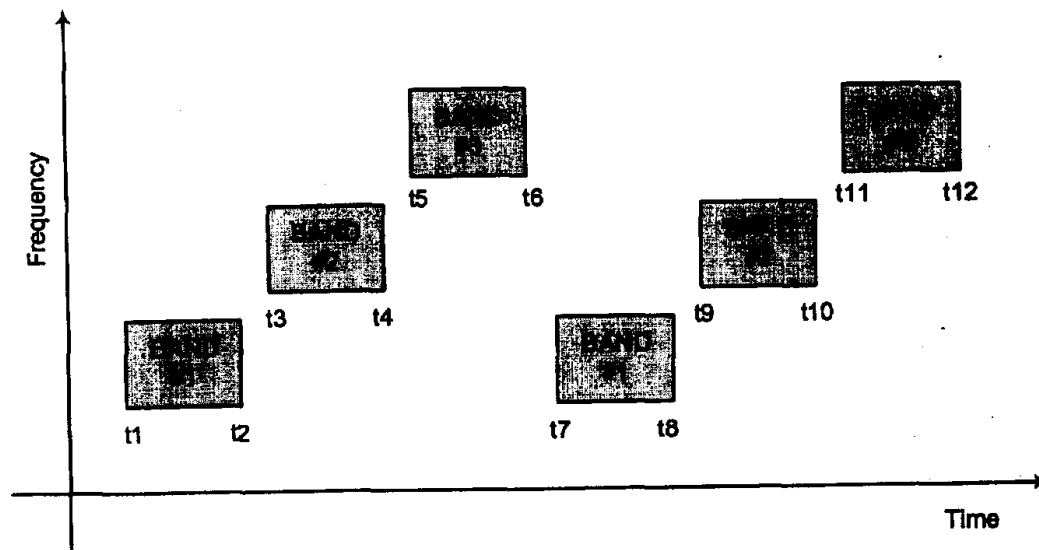
August 26, 2004

ATTACHMENT A

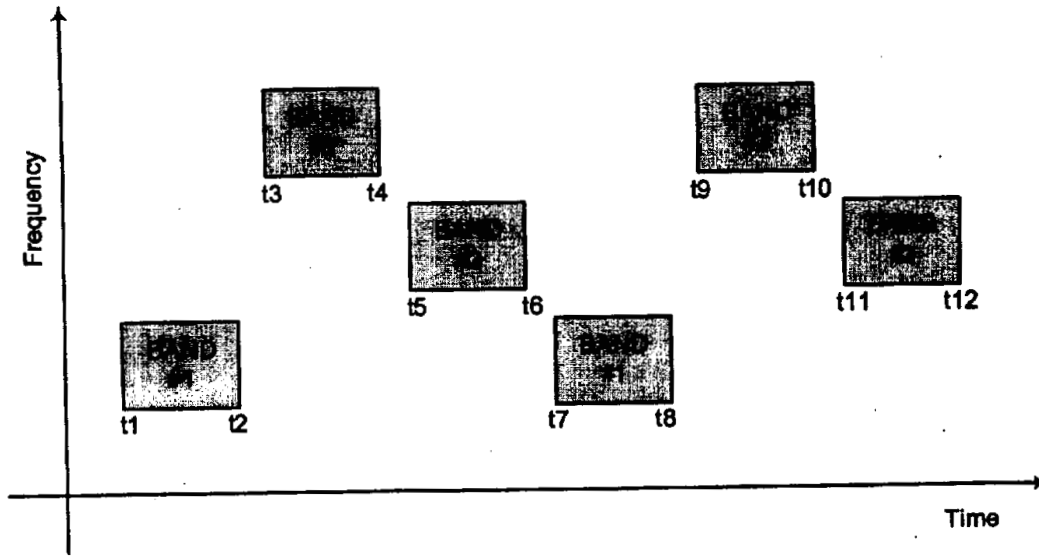
ATTACHMENT A

t1 = 0 ns
t2 = 242.4 ns
t3 = 312.5 ns
t4 = 554.9 ns
t5 = 625.0 ns
t6 = 867.4 ns
t7 = 937.5 ns
t8 = 1179.9 ns
t9 = 1250.0 ns
t10 = 1492.4 ns
t11 = 1562.5 ns
t12 = 1804.9 ns

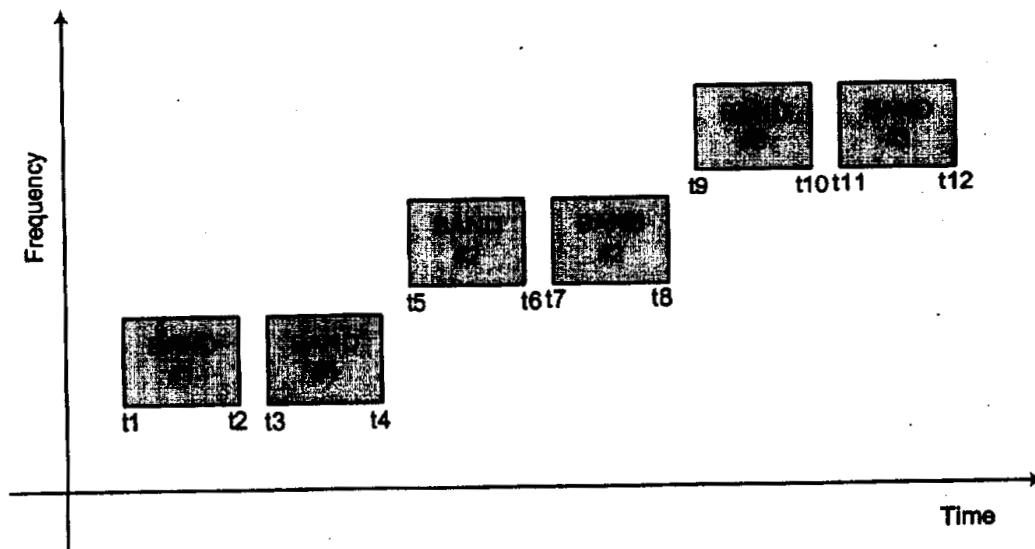
Time Frequency Code #1



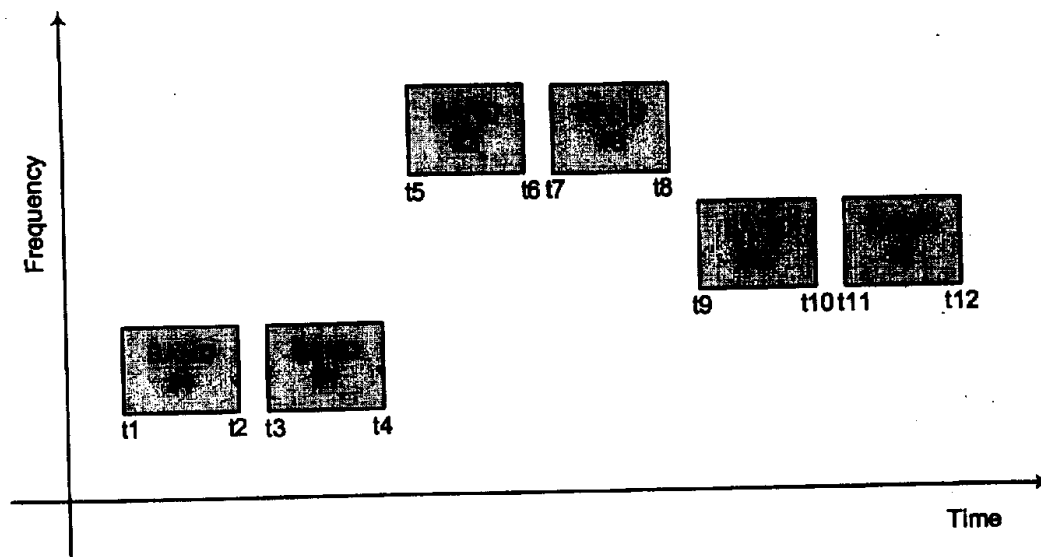
Time Frequency Code #2



Time Frequency Code #3



Time Frequency Code #4



ATTACHMENT B

ATTACHMENT B

Multi-Band OFDM
Waveform Summary

Excerpted from *IEEE P802.15-03/268r4 "Multi-Band OFDM Physical Layer Proposal for IEEE 802.15 Task Group 3a"* by Sanjay Mani, Tzero Technologies.

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1 Introduction

This description specifies the signal for a UWB system that utilizes the unlicensed 3.1 – 10.6 GHz UWB band, as regulated in the United States by the Code of Federal Regulations, Title 47, Section 15. The UWB system provides a wireless PAN with data payload communication capabilities of 53.3, 55, 80, 106.67, 110, 160, 200, 320, and 480 Mb/s. Transmitting and receiving at data rates of 53.3, 106.67, 110, and 200 Mb/s is mandatory. The proposed UWB system employs orthogonal frequency division multiplexing (OFDM). The system uses a total of 122 sub-carriers that are modulated using quadrature phase shift keying (QPSK). Forward error correction coding (convolutional coding) is used with a coding rate of 1/3, 11/32, 1/2, 5/8, and 3/4. The proposed UWB system also utilizes a time-frequency code (TFC) to interleave coded data over 3 frequency bands (called a band group). Four such band groups with 3 bands each and one band group with 2 bands are defined, along with four 3-band TFCs and two 2-band TFCs. Together, these band groups and the TFCs provide the capability to define eighteen separate logical channels or independent piconets. Devices operating in band group #1 (the three lowest frequency bands) are denoted Mode 1 devices, it shall be mandatory for all devices to support Mode 1 operation, with support for the other band groups being optional and added over time.

2 Time Domain Waveform

2.1 Mathematical description of the signal

The transmitted signals can be described using a complex baseband signal notation. The actual RF transmitted signal is related to the complex baseband signal as follows:

$$r_{RF}(t) = \text{Re} \left\{ \sum_{k=0}^{N-1} r_k(t - kT_{SYM}) \exp(j2\pi f_k t) \right\},$$

where $\text{Re}(\cdot)$ represents the real part of a complex variable, $r_k(t)$ is the complex baseband signal of the k^{th} OFDM symbol and is nonzero over the interval from 0 to T_{SYM} , N is the number of OFDM symbols, T_{SYM} is the symbol interval, and f_k is the center frequency for the k^{th} band.

All of the OFDM symbols $r_k(t)$ can be constructed using an inverse Fourier transform with a certain set of coefficients C_n , where the coefficients are defined as either data, pilots, or training symbols:

$$r_k(t) = \begin{cases} 0 & t \in [0, T_{CP}] \\ \sum_{n=-N_{ST}/2}^{N_{ST}/2} C_n \exp(j2\pi n \Delta_f)(t - T_{CP}) & t \in [T_{CP}, T_{FFT} + T_{CP}] \\ 0 & t \in [T_{FFT} + T_{CP}, T_{FFT} + T_{CP} + T_{GI}] \end{cases}$$

The parameters Δ_f and N_{ST} are defined as the subcarrier frequency spacing and the number of total subcarriers used, respectively. The resulting waveform has a duration of $T_{FFT} = 1/\Delta_f$. Shifting the time by T_{CP} creates the "circular prefix" which is used in OFDM to mitigate the effects of multipath. The parameter T_{GI} is the guard interval duration.

2.2 Subcarrier constellation mapping

The OFDM subcarriers shall be modulated using QPSK modulation. The encoded and interleaved binary serial input data shall be divided into groups of 2 bits and converted into complex numbers representing QPSK constellation points. The conversion shall be performed according to the Gray-coded constellation mappings, illustrated in Figure 1, with the input bit, b_0 , being the earliest in the stream. The output values, d , are formed by multiplying the resulting $(I + jQ)$ value by a normalization factor of K_{MOD} , as described in the following equation:

$$d = (I + jQ) \times K_{MOD}.$$

The normalization factor, K_{MOD} , is $1/\sqrt{2}$. In practical implementations, an approximate value of the normalization factor can be used, as long as the device conforms to the modulation accuracy requirements.

For QPSK, b_0 determines the I value and b_1 determines the Q value, as illustrated in Table 1.

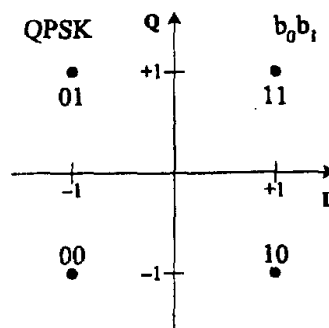


Figure 1 – QPSK constellation bit encoding

Table 1 – QPSK encoding table

Input bit ($b_0 b_1$)	I-out	Q-out
00	-1	-1
01	-1	1
10	1	-1
11	1	1

2.3 OFDM modulation

For information data rates of 53.3, 50, and 80 Mb/s, the stream of complex numbers is divided into groups of 50 complex numbers. We shall denote these complex numbers $c_{n,k}$, which corresponds to subcarrier n of OFDM symbol k , as follows:

$$c_{n,k} = d_{n+50 \times k} \quad n = 0, 1, \dots, 49, k = 0, 1, \dots, N_{\text{SYM}} - 1$$

$$c_{(n+50),k} = d_{(49-n)+50 \times k}^*$$

where N_{SYM} denotes the number of OFDM symbols in the MAC frame body, tail bits, and pad bits.

For information data rates of 106.7, 110, 160, 200, 320 and 480 Mb/s, the stream of complex numbers is divided into groups of 100 complex numbers. We shall denote these complex numbers $c_{n,k}$, which corresponds to subcarrier n of OFDM symbol k , as follows:

$$c_{n,k} = d_{n+100 \times k} \quad n = 0, 1, \dots, 99, k = 0, 1, \dots, N_{\text{SYM}} - 1$$

where N_{SYM} denotes the number of OFDM symbols in the MAC frame body, tail bits, and pad bits.

An OFDM symbol $r_{\text{data},k}(t)$ is defined as

$$r_{\text{data},k}(t) = \sum_{n=0}^{N_{\text{SD}}} c_{n,k} \exp(j2\pi M(n)\Delta_F(t - T_{\text{CP}})) + p_{\text{mod}(k,127)} \sum_{n=-N_{\text{ST}}/2}^{N_{\text{ST}}/2} P_n \exp(j2\pi m\Delta_F(t - T_{\text{CP}}))$$

where N_{SD} is the number of data subcarriers, N_{ST} is the number of total subcarriers, and the function $M(n)$ defines a mapping from the indices 0 to 99 to the logical frequency offset indices -56 to 56, excluding the locations reserved for the pilot subcarriers, guard subcarriers and the DC subcarrier (as described below):

$$M(n) = \begin{cases} n-56 & n=0 & n-49 & 50 \leq n \leq 53 \\ n-55 & 1 \leq n \leq 9 & n-48 & 54 \leq n \leq 62 \\ n-54 & 10 \leq n \leq 18 & n-47 & 63 \leq n \leq 71 \\ n-53 & 19 \leq n \leq 27 & n-46 & 72 \leq n \leq 80 \\ n-52 & 28 \leq n \leq 36 & n-45 & 81 \leq n \leq 89 \\ n-51 & 37 \leq n \leq 45 & n-44 & 90 \leq n \leq 98 \\ n-50 & 46 \leq n \leq 49 & n-43 & n=99 \end{cases}$$

The subcarrier frequency allocation is shown in Figure 2. To avoid difficulties in DAC and ADC offsets and carrier feed-through in the RF system, the subcarrier falling at DC (0^{th} subcarrier) is not used.

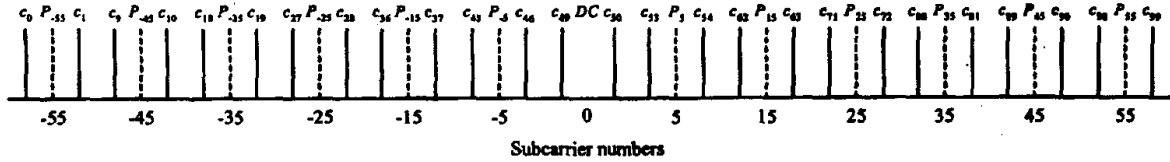


Figure 2 – Subcarrier frequency allocation

2.4 Pilot subcarriers

In each OFDM symbol, twelve of the subcarriers are dedicated to pilot signals in order to make coherent detection robust against frequency offsets and phase noise. These pilot signals shall be put in subcarriers numbered -55, -45, -35, -25, -15, -5, 5, 15, 25, 35, 45, and 55. The contribution due to the pilot subcarriers for the k^{th} OFDM symbol is given by the inverse Fourier Transform of the sequence $P_{n,k}$ below, which includes BPSK modulation by a pseudo-random binary sequence, p_l (defined further below), to prevent the generation of spectral lines.

$$P_{n,k} = P_{\text{mod}(k,127)} \times \begin{cases} \frac{1+j}{\sqrt{2}} & n=15,45 \\ \frac{-1-j}{\sqrt{2}} & n=5,25,35,55 \\ 0 & n=\pm 1, \dots, \pm 4, \dots, \pm 14, \pm 16, \dots, \pm 24, \pm 26, \dots, \pm 34, \pm 36, \dots, \pm 44, \pm 46, \dots, \pm 54, \pm 56 \end{cases}$$

For modes with data rates less than 106.67 Mbps:

$$P_{n,k} = P_{-n,k}^*, \quad n = -5, -15, -25, -35, -45, -55$$

2.7 Timing-related parameters

A list of the timing parameters associated with the OFDM PHY is listed in Table 2.

Table 2 – Timing-related parameters

Parameter	Value
N_{SD} : Number of data subcarriers	100
N_{SDP} : Number of defined pilot carriers	12
N_{SG} : Number of guard carriers	10
N_{ST} : Number of total subcarriers used	122 ($= N_{SD} + N_{SDP} + N_{SG}$)
Δ_f : Subcarrier frequency spacing	4.125 MHz ($= 528 \text{ MHz}/128$)
T_{FFT} : IFFT/FFT period	242.42 ns ($1/\Delta_f$)
T_{CP} : Cyclic prefix duration	60.61 ns ($= 32/528 \text{ MHz}$)
T_{GI} : Guard interval duration	9.47 ns ($= 5/528 \text{ MHz}$)
T_{SYM} : Symbol interval	312.5 ns ($T_{CP} + T_{FFT} + T_{GI}$)

3 Data Rate Modes and Convolutional Encoding

3.1 Rate-dependent parameters

The data rate dependent modulation parameters are listed in Table 3.

Table 3 – Rate-dependent parameters

Data Rate (Mb/s)	Modulation	Coding rate (R)	Conjugate Symmetric Input to IFFT	Time Spreading Factor (TSF)	Overall Spreading Gain	Coded bits per OFDM symbol (N_{CBPS})
53.3	QPSK	1/3	Yes	2	4	100
55	QPSK	11/32	Yes	2	4	100
80	QPSK	1/2	Yes	2	4	100
106.7	QPSK	1/3	No	2	2	200
110	QPSK	11/32	No	2	2	200
160	QPSK	1/2	No	2	2	200
200	QPSK	5/8	No	2	2	200
320	QPSK	1/2	No	1 (No spreading)	1	200
400	QPSK	5/8	No	1 (No spreading)	1	200
480	QPSK	3/4	No	1 (No spreading)	1	200

3.2 Convolutional Encoder

The convolutional encoder shall use the rate $R = 1/3$ industry-standard generator polynomials, $g_0 = 133_8$, $g_1 = 165_8$, and $g_2 = 171_8$, as shown in Figure 3. The bit denoted as "A" shall be the first bit generated by the encoder, followed by the bit denoted as "B", and finally, by the bit denoted as "C". The various coding rates are derived from the rate $R = 1/3$ convolutional code by employing "puncturing". Puncturing is a procedure for omitting some of the encoded bits in the transmitter (thus reducing the number of transmitted bits and increasing the coding rate) and inserting a dummy "zero" metric into the convolutional decoder on the receive side in place of the omitted bits. A puncturing pattern is illustrated in Figure 4. In each of these cases, the tables shall be filled in with encoder output bits from the left to the right. For the last block of bits, the process shall be stopped at the point at which encoder output bits are exhausted, and the puncturing pattern applied to the partially filled block.

Decoding by the Viterbi algorithm is recommended.

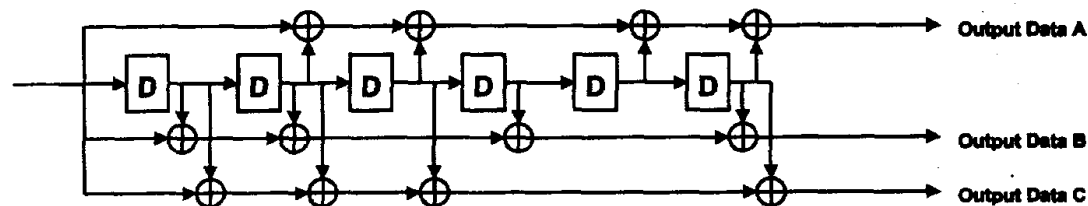


Figure 3 – Convolutional encoder: rate $R = 1/3$, constraint length $K = 7$

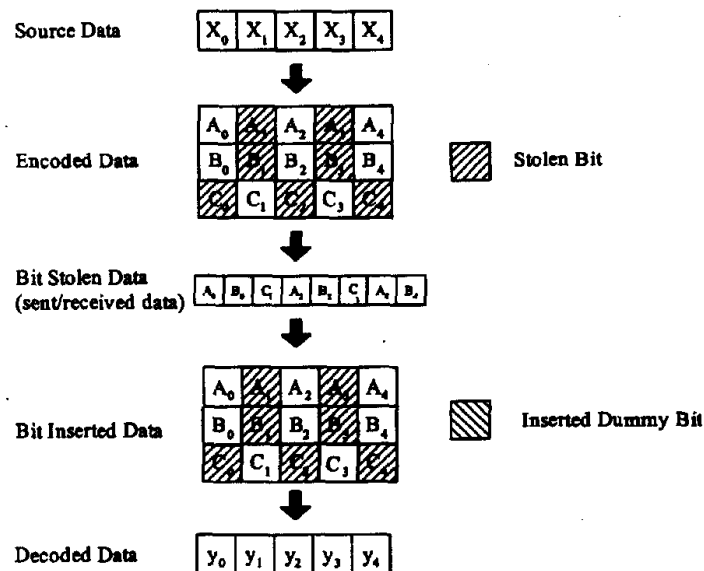


Figure 4 – An example of the bit-stealing and bit-insertion procedure ($R = 5/8$)

4 Operating band frequencies

4.1 Operating frequency range

This PHY operates in the 3.1 – 10.6 GHz frequency as regulated in the United States by the Code of Federal Regulations, Title 47, Section 15, as well as in any other areas that the regulatory bodies have also allocated this band.

4.2 Band numbering

The relationship between center frequency and band number is given by the following equation:

$$\text{Band center frequency} = 2904 + 528 \times n_b, n_b = 1 \dots 14 \text{ (MHz)}.$$

This definition provides a unique numbering system for all channels that have a spacing of 528 MHz and lie within the band 3.1 – 10.6 GHz. Based on this, five band groups are defined, consisting of four groups of three bands each and one group of two bands. Band group 1 is used for Mode 1 devices (mandatory mode). The remaining band groups are reserved for future use. The band allocation is summarized in Table 4.

Table 4 – OFDM PHY band allocation

Band Group	BAND ID	Lower frequency	Center frequency	Upper frequency
1	1	3168 MHz	3432 MHz	3696 MHz
	2	3696 MHz	3960 MHz	4224 MHz
	3	4224 MHz	4488 MHz	4752 MHz
2	4	4752 MHz	5016 MHz	5280 MHz
	5	5280 MHz	5544 MHz	5808 MHz
	6	5808 MHz	6072 MHz	6336 MHz
3	7	6336 MHz	6600 MHz	6864 MHz
	8	6864 MHz	7128 MHz	7392 MHz
	9	7392 MHz	7656 MHz	7920 MHz
4	10	7920 MHz	8184 MHz	8448 MHz
	11	8448 MHz	8712 MHz	8976 MHz
	12	8976 MHz	9240 MHz	9504 MHz
5	13	9504 MHz	9768 MHz	10032 MHz
	14	10032 MHz	10296 MHz	10560 MHz

The frequency of operation for Mode 1 devices is shown in Figure 5.

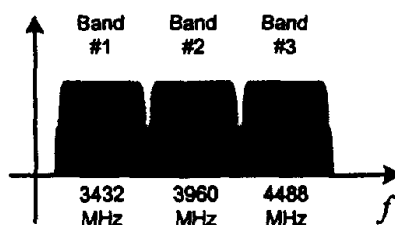


Figure 5 – Frequency of operation for a Mode 1 device.

4.3 Time Frequency Codes

Unique logical channels corresponding to different piconets are defined by using up to four different time-frequency codes for each band group. The time-frequency codes are defined in Table 5.

Table 5 – Time Frequency Codes and associated Preamble Patterns (Mode 1)

TFC Number	Mode 1: Length 6 Time Frequency Code					
	1	2	3	1	2	3
1	1	2	3	1	2	3
2	1	3	2	1	3	2
3	1	1	2	2	3	3
4	1	1	3	3	2	2

5 Transmitter Specifications

5.1 Transmit Power

The maximum average transmit power shall be -10.3 dBm.

5.2 Transmit PSD Mask

The transmitted spectrum shall have a 0 dBr (dB relative to the maximum spectral density of the signal) bandwidth not exceeding 260 MHz, -12 dBr at 285 MHz frequency offset, and -20 dBr at 330 MHz frequency offset and above. The transmitted spectral density of the transmitted signal shall fall within the spectral mask, as shown in Figure 6.

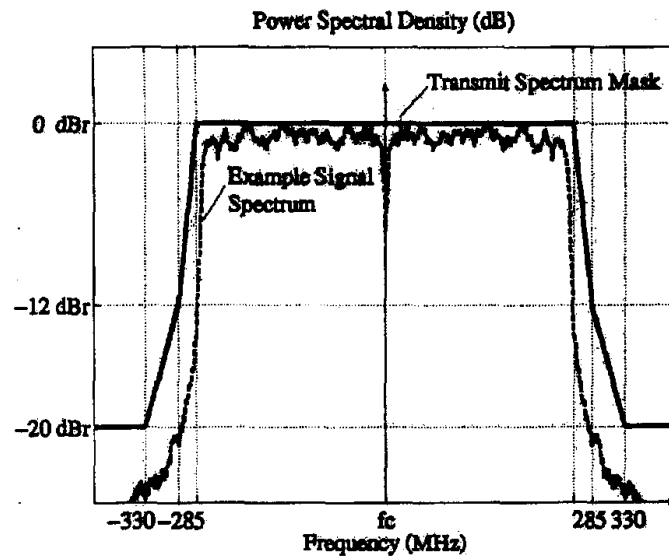


Figure 6 – Transmit Power Spectral Density Mask